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Research report

Neural sources of performance decline during continuous multitasking

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ABSTRACT

Multitasking performance costs have largely been characterized by experiments that involve two overlapping and punctuated perceptual stimuli, as well as punctuated responses to each task. Here, participants engaged in a continuous performance paradigm during fMRI recording to identify neural signatures associated with multitasking costs under more natural conditions. Our results demonstrated that only a single brain region, the superior parietal lobule (SPL), exhibited a significant relationship with multitasking performance, such that increased activation in the multitasking condition versus the singletasking condition was associated with higher task performance (i.e., least multitasking cost). Together, these results support previous research indicating that parietal regions underlie multitasking abilities and that performance costs are related to a bottleneck in control processes involving the SPL that serves to divide attention between two tasks.

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1. Introduction

Multitasking behavior is ubiquitous in today's technologically dense world (Foehr, 2006), and involves an attempt to accomplish a goal in the setting of another concurrent goal (Clapp & Gazzaley, 2010). Substantial evidence has shown multitasking performance deficits are characterized by response delays and errors, which result from attentional bottlenecks in cognitive processes such as perceptual encoding and response selection (Marois & Ivanoff, 2005; Pashler, 1994; Tombu et al., 2011). Several mechanisms have been proposed to underlie such bottlenecks, such as delays in distinct aspects of neural processing for the secondary task (e.g., stimuli identification, response selection, short term memory encoding) (Dux & Marois, 2009; Johnston, 1995; Pashler, 1994; Shapiro, Raymond, & Arnell, 1997), task-set reconfiguration (Rogers & Monsell, 1995), changing the weights in a competing cognitive system (Cohen, Dunbar, & McClelland, 1990; Gilbert & Shallice, 2002; Wylie, Javitt, & Foxe, 2004) or advanced preparation in task switching (Jamadar, Hughes, Fulham, Michie, &

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Karayanidis, 2010; Karayanidis et al., 2010). Neuroimaging research has suggested these sources of multitasking interference may arise from shared executive resources in widespread frontal and parietal regions that include the superior parietal lobule (SPL), inferior parietal sulcus, inferior frontal junction, inferior frontal sulcus, as well as subregions within the superior, middle and inferior frontal gyri (Deprez et al., 2013; Herath, Klingberg, Young, Amunts, & Roland, 2001; Hesselmann, Flandin, & Dehaene, 2011; Jiang, 2004; Takeuchi et al., 2013; Tombu et al., 2011). Characterizing the source of interference that underlies multitasking costs has largely involved experimentation using two punctuated perceptual/response tasks (psychological refractory period – PRP paradigm: Telford, 1931,Welford, 1952; Pashler & Johnston, 1989; Pashler, 1994; Task-switching paradigm: Jersild, 1927; Rogers & Monsell, 1995; Kiesel, Steinhauser, Wendt, Falkenstein, & Jost, 2010). Thus, it is less clear whether similar neural regions are also associated with performance declines during a continuous multitasking paradigm, as is more common to everyday life.

The use of a continuous performance paradigm as a primary task may reveal unique features regarding task switching that occurs under more natural conditions compared to the discrete presentation paradigms routinely used to study multitasking. Continuous tasks have been shown to engage perception, visual-spatial deployment, and response-selection in parallel (Rushworth, Johansen-Berg, Göbel, & Devlin, 2003), providing a more naturalistic design that is not driven by discrete task structures. As previously described, typical instructions dictate an artificial task switch by imposing a constraint of performing separate responses to observe task switching (Pashler, 1994). Given that response order constraints have been shown to greatly increase multitasking costs (Israel & Cohen, 2011; Levy & Pashler, 2001; Ruthruff, Hazeltine, & Remington, 2006), here we use a continuous primary task to make response order instruction unnecessary.

To assess the neural correlates of multitasking performance decline, we collected functional magnetic resonance imaging (fMRI) data while participants were engaged in a custom-designed video game (NeuroRacer) (Anguera et al., 2013). Consistent with many memory and attention tasks (e.g., working memory: digit symbol task, speed of processing: letter comparison, pattern comparison) that have been shown to exhibit linear declines with age (Grady, Springer, Hongwanishkul, McIntosh, & Winocur, 2006; Park et al., 2002), we have shown that continuous multitasking, as assessed via NeuroRacer, also results in performance declines across the adult lifespan (Anguera et al., 2013). Therefore, here we examined individuals in the 4th and 5th decades of life (30 yo & 40 yo), when significant decline has already begun. Neural and performance data was contrasted between a single task (sign detection) and a dual task (sign detection while driving a virtual car). Although widespread fronto-parietal regions have been previously associated with multitasking cost during two punctuated tasks, we designed this study to examine whether similar regions would be associated with multitasking performance declines when single and dual tasks are perceptually matched and is continuous in nature.

2. Methods

2.1. Participants

Thirty-one healthy, right-handed participants between 30 and 49 y.o. (mean age 38.4 ± 6.3 y, 14 females) took part in this experiment. All participants had normal or corrected-to-normal vision, gave informed written consent, and were monetarily compensated for participation in the study. All participants were screened to ensure they had no history of neurological or psychiatric disorders, not depressed, did not have strabismus or amblyopia, no history of substance abuse and were free of medication. Additionally, all participants were considered to be non-video game players, as defined by having less than 2 h of any type of video-game usage per month in the past two years. Approval of the study was given by the Committee on Human Research at the University of California, San Francisco.

2.2. Paradigm

Task stimuli were presented on a 32″ monitor placed at the back of the fMRI scanner bore and viewed via a headcoil-mounted mirror. Participants engaged in a custom designed video game ('NeuroRacer'; Anguera et al., 2013) using a Current Designs game controller to control tracking (i.e., driving the car; right forefinger and thumb) and responding to sign stimuli (left index finger).

2.2.1. Tasks

The visuomotor tracking, or Drive Only (DO), task (Fig. 1A) involved keeping a car as accurately as possible within a target box drawn on a continuously moving road. A pseudo-randomized, counterbalanced selection of road segments (that is, right/left turns & inclining/declining hills) formed the tracks, with turn/hill severity being either mild or severe. The discrimination, or Sign Only (SO), task (Fig. 1B) involved responses to visual stimuli presented for 400 msec, two degrees above a fixation cross. During SO, participants were instructed to respond as quickly and accurately as possible only to green circles (33% frequency) with a right button press. Distractor (non-target) signs included an equal distribution of red or blue circles, as well as triangles, squares or pentagons that could be colored green, red or blue. In the 'Sign with Road' task (SWR; single task; Fig. 1C), the car was on autopilot and participants responded to the target signs as during SO. In the 'Sign and Drive' task (SD; dual task; Fig. 1D), participants were told to respond to the target signs (as in SO) and continuously drive (as in DO). The SWR and SD tasks served as our tasks of interest, as they were perceptually matched and only differed in task requirements (single or dual task). Sign discrimination events always coincided exactly with a road segment change and occurred randomly with a stimulus-onset-interval randomized between 4 and 12 sec. Road segment changes occurred randomly with a stimulus-onset-interval randomized between 2 and 4 sec. Thus, road segment changes occurred more frequently than sign events and helped minimize participants' ability to form expectations for sign event

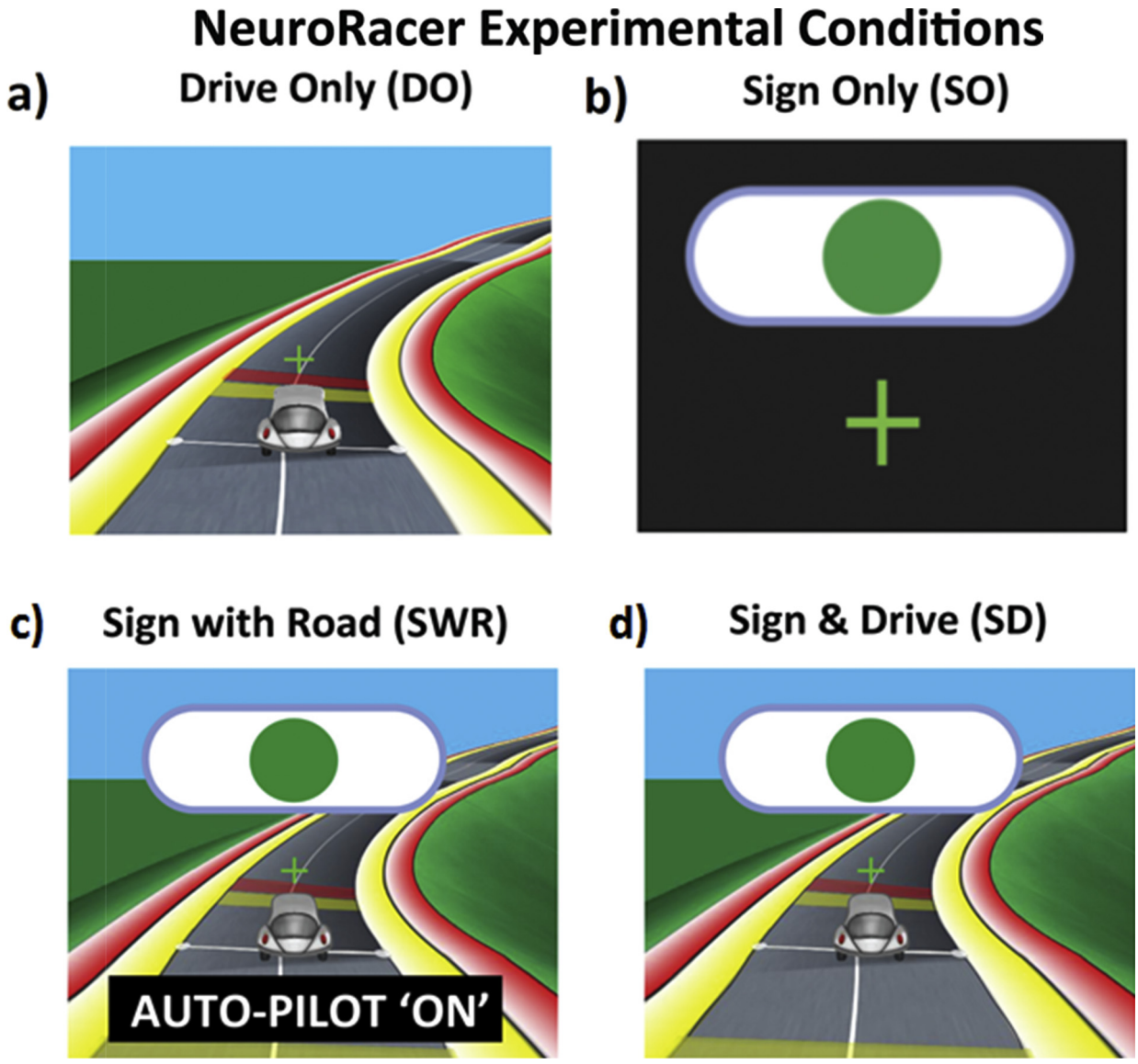

Fig. 1 – NeuroRacer tasks and experimental design. Screenshots of experimental conditions. A.) The Drive Only (DO) condition was used to establish a titrated driving level setting of no distraction for each participant in the scanner. B.) The Sign Only (SO) was used to establish an individualized response time discrimination window for each participant in the scanner. C.) The Sign with Road (SWR) condition contained the discrimination task with the driving task presented passively in the background. The car followed an idealized, autopiloted path while the participant engaged in the discrimination task. Note: the displayed text "auto-pilot on" is for display purposes only and was not present during the experiment. D.) The Sign & Drive (SD) contained both tasks simultaneously and was and was interrogated along with SWR during the testing phase of the experiment as our multitasking condition.

onset as attention was more consistently drawn towards the driving task in response to road segment changes. Furthermore, sign events coincided with road segment changes to ensure both tasks (driving and sign detection) required simultaneous attention from the participant.

Participants were instructed to fixate at the center of the screen at all times. Real-time feedback was indicated by a 100 msec color change of the fixation cross one second after stimulus presentation (green for correct, red for incorrect) and/or by a shaking of the fixation cross when the car was outside the target-tracking zone. Each experimental run lasted about 180 sec and contained 21 stimuli. Each run was preceded by instructions cueing the condition and ended with a performance feedback summary. There was a total of six experimental blocks with each block consisting of one experimental run of each of the four tasks (i.e., 4 runs per block). For feedback purposes, correct responses to the appropriate signs within the thresholded response time

window (see below) were categorized as hits. Non-responses, late responses or mismatched key presses to stimuli were counted as incorrect.

2.2.2. Thresholded performance

Prior to the experimental runs, participants underwent an adaptive thresholding procedure to assess perceptual discrimination and visuomotor tracking abilities performed in isolation (i.e., DO and SO tasks; Fig. 1A,B). For discrimination, a staircase algorithm changed the time window that allowed for a correct response during each of the nine 120 sec runs, containing 48 signs per run. For the visuomotor tracking task, the speed of the road was thresholded with a similar staircase algorithm over twelve 60-sec runs (for more details, see Anguera et al., 2013). Upon completion of each thresholding block, difficulty levels were interpolated across runs to identify the task parameters that resulted in 80% single task performance for each individual participant's discrimination and tracking ability. The difficulty of the experimental tasks were set to these individualized levels for each participant so that they engaged in each condition at a level appropriate for their ability, thus facilitating a fairer comparison of multitasking performance across individuals. This thresholding procedure was performed in the fMRI scanner to replicate the environment where they would be performing the experiment.

2.3. Behavioral data analysis

Behavioral data was analyzed for both conditions using paired *t*-tests. Analysis of response time data included all correct trials, regardless of the thresholded time window used for feedback. Similarly, accuracies were calculated regardless of the thresholded time window, and analysis of accuracy data included correct hits and correct rejections (i.e., withholding response to non-targets). All behavioral data were analyzed using SPSS 20 for Windows.

Multitasking costs were calculated by subtracting the single task (SWR) data from the multitasking (SD) data. This multitasking cost metric was later used to assess a neuro–behavioral correlation of multitasking declines.

2.4. fMRI acquisition and processing

All images were acquired on a Siemens 3T Trio Magnetom. Echo planar imaging data was collected with a 2.1-sec repetition time and 1.8 × 1.8 × 3 mm voxel size using 32 oblique axial T2*-weighted gradient-echo slices (repetition time 2,100 msec; echo time 25 msec; 90° flip angle; field of view = 23 cm, 96 × 96 matrix). Images were corrected for slice timing, motion artifacts, and Gaussian-smoothed to 5-mm FWHM. Data were modeled using a general linear model (GLM) in SPM8 in participant-averaged space and included regressors for six motion parameters (X, Y, Z, roll, pitch, yaw). Group whole-brain maps were calculated from MNI-normalized data. In addition, high-resolution anatomical (T1-MPRAGE) datasets were collected (1 × 1 × 1 mm voxel size, field of view = 160 × 240 × 256 mm, repetition time = 2300 msec, echo time = 3 msec, flip angle = 9°).

2.5. fMRI univariate analysis

Blood oxygen level dependent (BOLD) signal change was modeled for all four conditions with a block design through a GLM as condition-specific box-car functions convolved with a canonical hemodynamic response function. We conducted a univariate contrast between our two conditions of interest (SD − SWR). A voxel-by-voxel *t*-test comparison between SD and SWR revealed brain regions specifically involved in multitasking, thus minimizing effects related to discrimination, which was common to both conditions. Whole-brain statistical corrections for multiple comparisons were done by thresholding *p*-values with a cluster extent determined by a Monte Carlo simulation, resulting in a corrected *p*-value <.05.

2.6. Neurobehavioral correlation analysis

In order to more directly assess which regions may be related to the performance based multitasking cost, we conducted correlations between the changes in BOLD activity (β parameter estimates) between the two conditions (SD − SWR) with the cost of multitasking performance (change in response time, SD − SWR). This analysis was conducted for the voxels listed in Table 1 and corrected for multiple comparisons using the threshold procedure detailed in the methods.

3. Results

3.1. Behavioral

A *t*-test of the mean response times (SWR: 513.9 msec, SD: 530.7 msec) revealed significantly slower responses during SD compared to SWR [$t_{(30)} = 3.77$, $p = .00042$, Cohen's d = .194]. Mean accuracy (SD: .967, SWR: .964) showed no significant differences between these two conditions [$t_{(30)} = -.262$, $p = .795$, Cohen's d = .0265]. Response time slowing, as an index of multitasking cost (as calculated by SD − SWR), did not show a significant correlation with age [$t_{(30)} = -1.69$; $p = .167$] nor did it show a significant difference with gender [$t_{(30)} = -1.46$, $p = .10$, Cohen's d = .004].

3.2. Neuroimaging results

3.2.1. Whole brain analysis

We conducted a whole-brain univariate contrast between the two conditions of interest (SD − SWR). The comparison between SD and SWR revealed multiple regions that were more engaged during multitask performance (i.e., SD > SWR; Table 1). These regions included areas involved in pre-motor and motor cortex, likely for the additional demands of the driving task (Table 1). Also, visual regions, parietal and frontal regions demonstrated greater activity, likely as a result of additional task requirements, multitask management and task switching (see Table 1 and Fig. 2). With the exception of the bilateral temporal lobe, which has been suggested to be involved with complex perception (Olson, Plotzker, & Ezzyat, 2007), no regions exhibited greater activity during SWR compared to SD.

Table 1 – Summary of univariate analysis. Regions showing significant β-value contrast differences between Sign with Road (SWR) and Signs with Drive (SD) following cluster correction.

	Brain region	Volume (mm^3)	Center of Mass		
			x	y	z
Frontal	Left Precentral Gyrus	45280	−28	−20	58
	Right Superior Frontal Gyrus	13960	20	−4	60
	Right Precentral Gyrus	1920	58	8	26
Parietal	Right Superior Parietal Lobule	7672	26	−50	54
	Left Precentral Gyrus	1824	−58	6	28
	Left Central Opercular Cortex	576	−46	0	4
	Right Precentral Gyrus	472	12	−18	48
Occiptal	Left Lateral Occipital Cortex, Inferior Division	1976	−42	−70	6
	Right Lateral Occipital Cortex, Inferior Division	936	44	−68	4
	Left Lingual Gyrus	368	−10	−72	−2
	Left Lateral Occipital Cortex, Superior Division	360	−20	−76	40
	Left Intracalcarine Cortex	352	−6	−76	18
Temporal	Right Temporal Pole	1264	32	10	−26
	Left Temporal Pole	408	−32	8	−28
Subcortical	Left Thalamus	2640	−16	−18	8
	Right Cerebellum	1522	16	−54	−20

3.3. *Correlations*

We observed fronto-parietal regions to be more engaged during the multitasking condition compared to singletasking. In order to assess whether these regions were related to performance-based multitasking cost, we conducted regression analysis between the differences in BOLD activity (β parameter estimates) between the two conditions (SD – SWR) and the multitasking performance cost (change in response time, SD – SWR). This analysis was conducted only using data from the regions listed in Table 1 and corrected for multiple comparisons using the threshold procedure detailed in the methods.

Interestingly, only one cluster survived statistical correction, the right superior parietal lobule (SPL; center of mass: [−25 −49 53]; Fig. 3). Even following outlier exclusion, the right

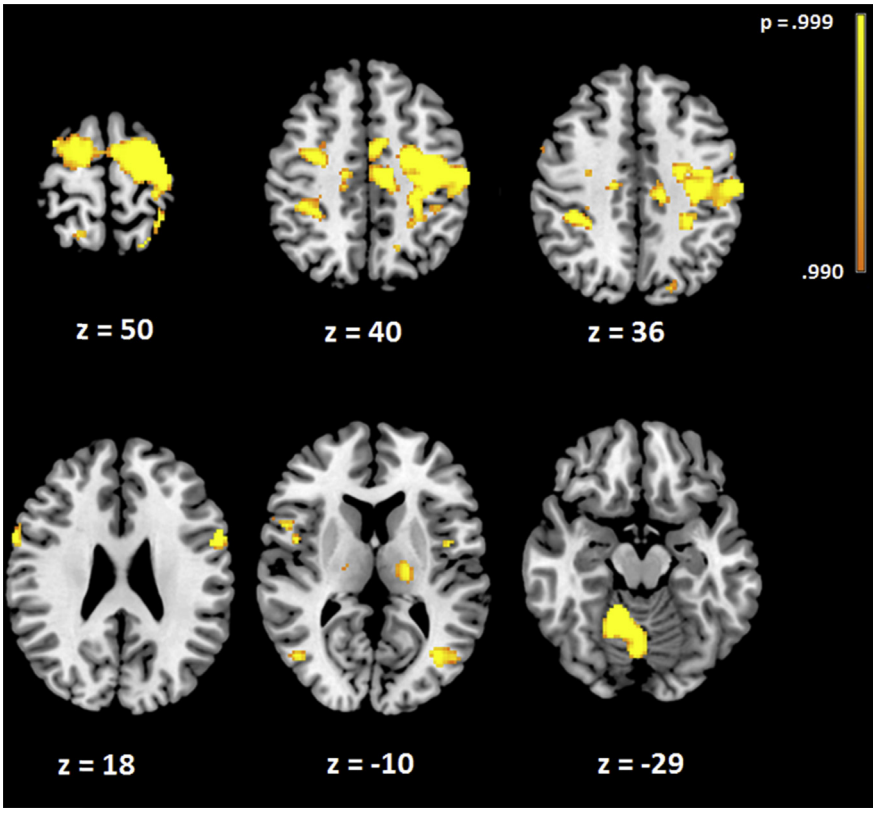

Fig. 2 – Whole-brain, cluster-corrected univariate analysis between the two NeuroRacer conditions, SD and SWR. (z = −29, −10, 18, 36, 40, 50).

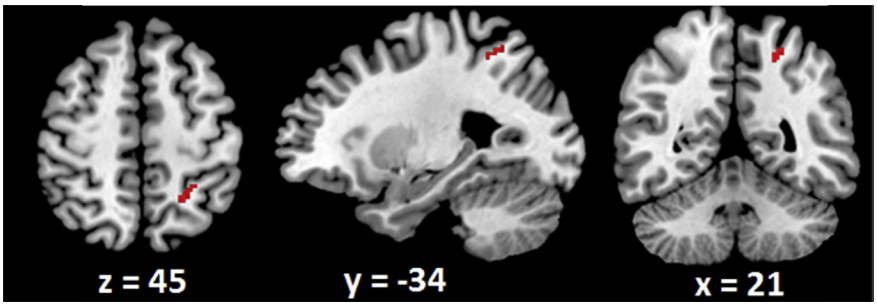

Fig. 3 – Whole-brain cluster-corrected neurobehavioral correlation analysis conjoined with the contrast analysis. (z = x = 21, y = −34, z = 45).

SPL demonstrated a significant correlation ($r = -.37$, $p < .05$; Fig. 4), such that participants who utilized right SPL more during multitasking compared to singletasking exhibit less multitasking performance cost. This suggests that engagement of the right SPL is involved in mitigating multitasking performance delays and thus may serve as a bottleneck in multitasking performance.

Additionally, activity in this cluster did not correlate with RT within the SWR (single task) condition ($p = .39$) nor within the DS condition ($p = .69$).

4. Discussion

The current results identified widespread neural activity largely across frontal, parietal and visual regions, associated with a continuous multitasking paradigm. However, only one region, the SPL, demonstrated a relationship with multitasking performance, such that increased activation occurred in top performers (participants having the least multitasking cost). Together, these results support previous research indicating fronto-parietal regions underlie multitasking abilities and that multitasking performance costs may be related to a bottleneck in executive processes involving the SPL.

Previous studies have shown the superior parietal region to be involved in top-down attentional control (Corbetta & Shulman, 2002), which occurs in anticipation of stimulus onset (Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008). Importantly, the current results support previous research showing increased SPL activity during multitasking and task switching (Braver, Reynolds, & Donaldson, 2003; Jaeggi, Buschkuehl, & Etienne, 2007; Kimberg, Aguirre, & D'Esposito, 2000; Nebel et al., 2005; Szameitat, Schubert, Müller, & Von Cramon, 2002). Here, we extend these findings to show that

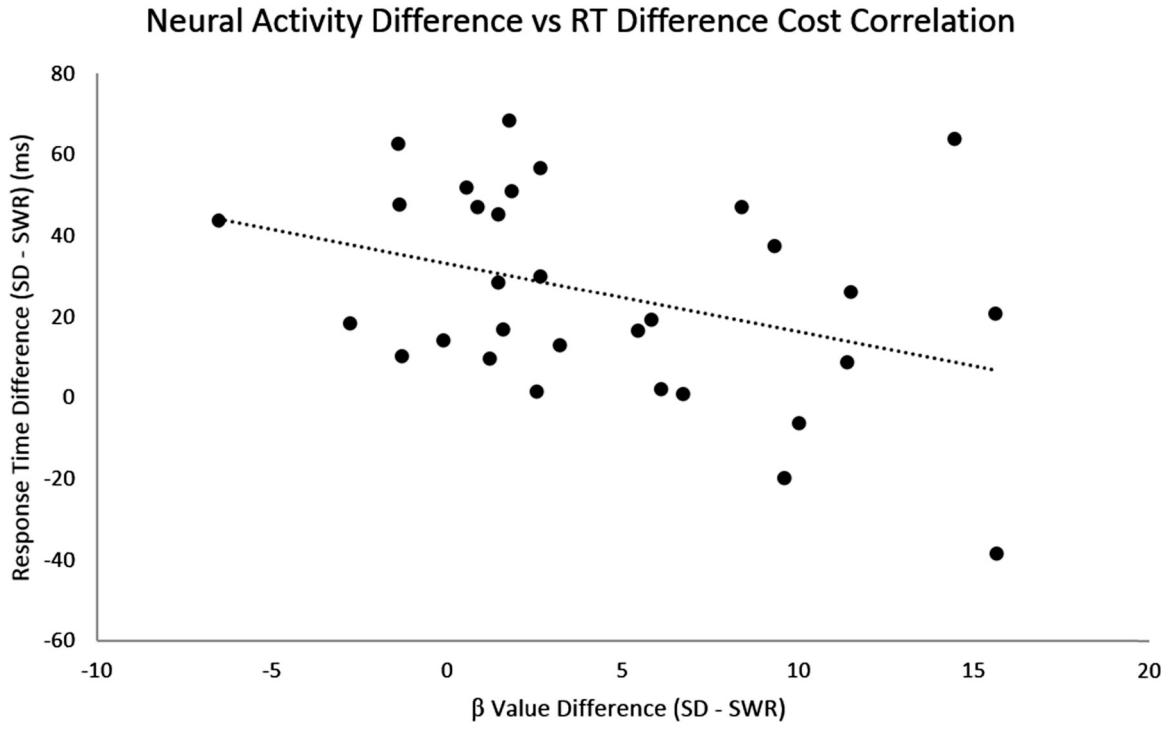

Fig. 4 – Correlation plots of RT differences (SD – SWR) versus β-value differences (SD – SWR).

during continuous multitasking, increased SPL activity is related to improved multitasking performance. Thus, increased SPL activity may reflect enhanced attentional engagement or cognitive control processes that serve to efficiently switch between the primary and secondary tasks, which is thought to give rise to a bottleneck in multitasking performance (Dux & Marois, 2009; Johnston, 1995; Pashler, 1994; Shapiro et al., 1997). Specifically, in our task, increased SPL activity may reflect increased response representation for the interrupting task in order to mitigate task set interference by advanced implementation of the relevant interrupting sign task stimulus-response set (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Jamadar et al., 2010; Karayanidis et al., 2010).

Other studies have shown SPL to be involved with increased motor demands (Rémy, Wenderoth, Lipkens, & Swinnen, 2010; Rushworth et al., 2003) as well as perceptual and response-decision aspects (Marois, Larson, Chun, & Shima, 2006). Therefore, it could be argued that SPL activity was increased due to additional perceptual and response demands rather than a reflection of cognitive control. Given that both the single and dual task conditions were perceptually matched, it is unlikely that the SPL was responding to perceptual differences. However, we cannot completely rule out SPL activity as a response to motor demands, as continually driving a car during the sign detection task certainly increased motor demands. Yet, this interpretation is not independent from our interpretation that SPL is involved in cognitive control processes that underlie task switching, which is a switch between motor demands. Nonetheless, if SPL activity were more involved in the motor execution process itself, rather than higher cognitive control, we would expect to see similar relationships between neural activity and multitasking performance in other motor related regions such as the precentral gyrus and cerebrellum (see Table 1), but this was not observed. Additionally, SPL activity only correlated with the change between tasks and did not correlate with response times in the singletasking or multitasking conditions, which might be expected if SPL responded to motor demands. Moreover, it should be noted that transcranial magnetic stimulation to the SPL has provided causal evidence that this region is involved in visuospatial judgements (Kanai, Dong, Bahrami, & Rees, 2011; Sack et al., 2007) as well as resolving perceptual conflicts (Kanai, Bahrami, & Rees, 2010). Our current results, in light of previous research, would suggest that SPL may enhance performance during continuous multitasking by optimally allocating visuospatial attention when needed, as a form of advanced preparation of task switching (Jamadar et al., 2010; Karayanidis et al., 2010).

Our task uses a continuous visuomotor tracking task to generate continuous engagement and stimuli with a forced choice perceptual discrimination task as a punctuated interruptor, a scenario that is more reflective of complex acts of real-world multitasking. Typically, multitasking paradigms employ explicit instructions for participants to respond to each task separately (that is, not to both at the same time) even when they perfectly overlap in time. In this paradigm, explicit instructions about response order are moot as participants naturally switch between tasks as fast and accurately as possible, thus avoiding contamination of task ordering instructions and emphasizing the discrimination task more as an interruptor. It is possible the constant visual attention and response demands required for a continuous task differs from discrete task execution (Pashler, 1994; Rushworth et al., 2003) by allowing more flexibility in scheduling/allocating parallel processes (Van Mier, Hulstijn, & Petersen, 1993) and may be more revelatory of intrinsic multitasking delays. The present experimental design supports findings of a multitasking delay with an interruptor in the context of a continuous task, providing a novel vantage point to understand previous multitasking findings in a more dynamic environment. Yet, it could be argued that because the continuous multitasking paradigm did not alter accuracy, the real-world significance of the observed response time slowing and SPL activity during multitasking may be limited. However, it should be noted that this continuous multitasking paradigm mimics driving down the road while attending to street signs. If a real-world driver exhibits a slowed response time to a relevant warning sign (e.g., stop sign, stop light, brake light), this could be the difference between a safe stop and an accident. In this common scenario, it is not sufficient to merely detect the sign accurately, it is of critical importance to detect the sign promptly. Here we provide evidence that the SPL plays a prominent role in continuous multitasking where response time is of the utmost importance.

Conflict of interest

None.

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